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# 3-D reconstruction of active regions with STEREO

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ABSTRACT

We review data analysis and physical modeling related to the 3-D reconstruction of active regions in the solar corona, using stereoscopic image pairs from the STEREO/EUVI instrument. This includes the 3-D geometry of coronal loops (with measurements of the loop inclination plane, coplanarity, circularity, and hydrostaticity), the 3-D electron density and temperature distribution (which enables diagnostics of hydrostatic, hydrodynamic, and heating processes), the 3-D magnetic field (independent of any theoretical model based on photospheric extrapolations), as well as the 3-D reconstruction of CME phenomena, such as EUV dimming, CME acceleration, CME bubble expansion, and associated Lorentz forces that excite MHD kink-mode oscillations in the surroundings of a CME launch site. The mass of CMEs, usually measured from white-light coronagraphs, can be determined independently from the EUV dimming in the CME source region. The detailed 3-D density and temperature structure of an active region can be modeled using the method of instant stereoscopic tomography with orders of magnitude higher spatial resolution than with standard solar-rotation tomography.



## 1. Introduction

The importance of three-dimensional (3-D) reconstruction in astrophysics can hardly be overstated. Without stellar parallax measurements we would not know the distance to the stars, we would not be able to tell apart supernovas from our milky way from those of other galaxies, nor would we know about the expanding universe. Similarly, the STEREO mission has opened up our 3-D vision on the Sun and in the heliosphere, where we can use the stereoscopic parallax to triangulate coronal loops (Feng et al., 2007a; Aschwanden et al., 2008a), active regions, polar plumes (Feng et al., 2009), polar jets (Patsourakos et al., 2008), filaments (Gissot et al., 2008; Liewer et al., 2009), prominences, and coronal mass ejections (e.g., Wood et al., 2009). 3-D reconstruction of structures in the solar corona has been attempted already in the pre-STEREO era, using solar-rotation stereoscopy and tomography (e.g., Berton and Sakarai, 1985; Koutchmy and Molodensky, 1992; Aschwanden and Bastian, 1994; Frazin, 2000), but this approach requires quasi-stationary structures over a time interval of a quarter solar rotation ( $\approx 7$ days), which are hard to find in the highly dynamic corona. However, solar-rotation-based stereoscopy is adequate to reconstruct large-scale 3-D coronal structures, such as coronal holes and streamers (e.g., Wang et al., 2000; Saez et al., 2007; Zhukov et al., 2008). A particular method of "dynamic stereoscopy" was developed that allows for dynamic plasma flows along coronal loops, but relies on the quasi-stationarity of the guiding magnetic field (Aschwanden et al., 1999a). Only after the launch of the STEREO mission (October 2006) we obtained simultaneous stereoscopic image pairs that allow us to apply triangulation methods to measure directly the 3-D geometry of coronal structures, using the *Extreme Ultra-Violet Imager* (*EUVI*) (Wülser et al., 2004), which is part of the SECCHI instrument suite (Howard et al., 2008). The two STEREO spacecraft are continuously separating by $\approx 45^\circ$ per year, but classic stereoscopy is most favorable at small separation angles ( $\lesssim 30^\circ$), which occurred during the first year of the mission. In this review we focus on the 3-D reconstruction of active regions, which are interesting plasma physics laboratories in their own right, as well as hotbeds for coronal mass ejections (CMEs), the major science focus of the STEREO mission. Some recent reviews on 3-D reconstruction with STEREO data describe theoretical modeling approaches (Aschwanden et al., 2008d), the current status of solar stereoscopy (Wiegelmann et al., 2009), or solar flare and CME observations with STEREO/EUVI (Aschwanden et al., 2009c). The content of this review is organized according to different physical parameter regimes that are explored in stereoscopic 3-D reconstructions of active regions, such as the 3-D geometry (Section 2), the 3-D electron density (Section 3), the 3-D electron temperature (Section 4), the 3-D magnetic field (Section 5), as well as the 3-D evolution of EUV dimming (Section 6) and the 3-D motion of oscillating loops (Section 7) which both accompany the launch of CMEs.

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## 2. 3-D geometry of active regions

The coronal plasma is very inhomogeneous, in particular in active regions, where strong magnetic fields confine the plasma within curved coronal flux tubes. Based on the assumption of a low value of the coronal plasma-$\beta$ parameter, which states that the magnetic pressure is much higher than the thermal pressure, we can conceptualize an active region in terms of numerous thermally isolated flux tubes, which essentially are one-dimensional (1D) structures with relatively small cross-sections, so they have a high length-to-width aspect ratio of $l/w \approx 10, \ldots, 10^3$. Consequently, the plasma confined in these coronal flux tubes, simply called "loops", represent mini-atmospheres that have their own hydrodynamic structure each, and can be modeled as simple isolated 1D flux tubes. This particular nature of the magnetic field allows us to characterize coronal loops as curvi-linear 1D structures, which can conveniently be triangulated with STEREO. However, there are a number of problems that make the stereoscopic triangulation not so simple that it can be automated with a software algorithm. First of all, there exists no completely isolated loop, each one is surrounded by thousands of other loops or diffuse plasma that add confusion to the discrimination of a selected loop from the background. Therefore, only loops that have sufficient contrast in electron density and/or temperature from the surrounding background can be triangulated. Second, the identification of corresponding loops in a stereoscopic image pair A and B is often ambiguous, especially for large separation angles when the images A and B look very dissimilar. Thus, small separation angles in the order of $\alpha_{sep} \approx 5^\circ - 15^\circ$ are preferable. This requirement makes the first few months of the mission, i.e., April–June 2007, most suitable. Stereoscopy with larger separation angles is in principle possible if an approximate 3-D magnetic field can be modeled, but has not yet been attempted. A third difficulty is the confusion of loop-unrelated structures in active regions, in particular bright "moss" regions (Berger et al., 1999; DePontieu et al., 2009) that cover the central base of an active region. The moss in EUV is nothing else than the cooler transition regions ($T \approx 1-2$ MK) at the footpoint of hotter loops ($T \approx 2-8$ MK) and interferes with stereoscopic triangulation of small-scale loops in the center of active regions. A fourth difficulty is the hydrostatic scale height, which makes loops visible in EUV only within the lowest density scale height, which is approximately up to a height of $h \lesssim 50-100$ Mm for $T = 1-2$ MK loops. The resulting lack of contrast at the loop apex makes it often impossible to trace the connectivity between magnetically conjugated footpoints of the same loop, except if the loop is highly inclined. All these restrictions should be kept in mind when a stereoscopic 3-D reconstruction of an active region is attempted, because it explains the biases for large inclined loops, the lack of short small-scale loops, and the missing apices of vertically oriented loops.

In Fig. 1 we show an example of a stereoscopic reconstruction of the 3-D geometry of some 70 loops in active region NOAA 10955, observed on 9 May 2007 with STEREO/EUVI in the wavelengths of 171, 195, and 284 Å when the STEREO spacecraft had a separation of $\alpha_{sep} \approx 7.3^\circ$. The vertical projection (Fig. 1, top left) clearly illustrates the altitude cutoff at $h \lesssim 0.1 R_\odot$ due to the hydrostatic scale height condition. The lateral projection along the dipole axis of the active region (Fig. 1, bottom right) visualizes the high inclination angles of complete loops, while there is no complete vertical large loop present, which is also a consequence of the "hydrostatic visibility condition".

The 3-D reconstruction of such a set of coronal loops that represent the skeleton of an active region involves a number of

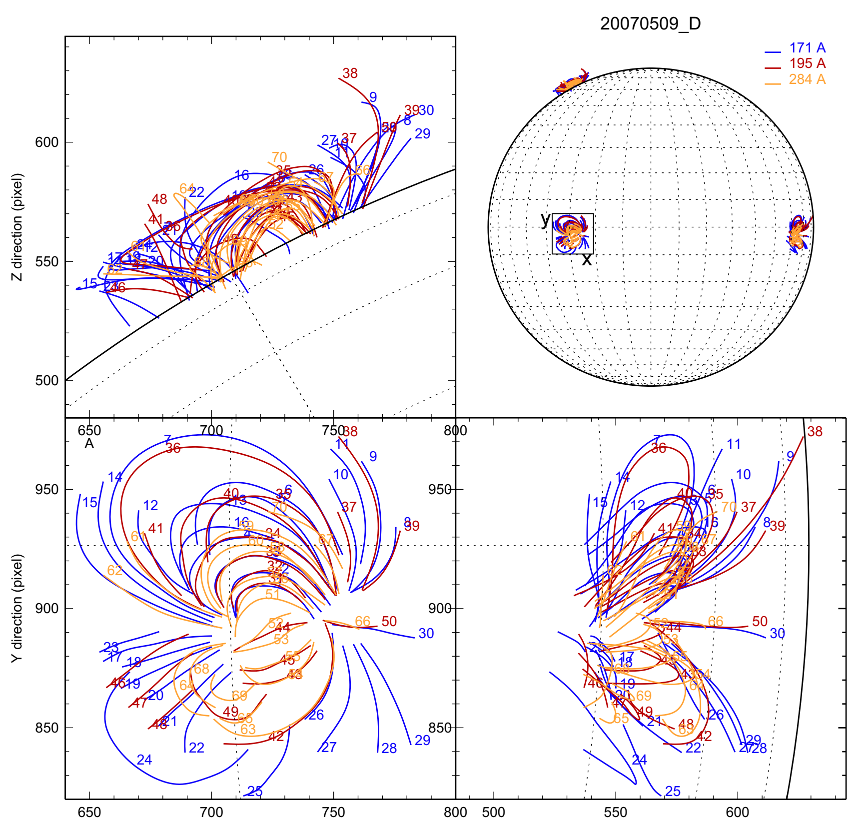


**Fig. 1.** Orthogonal projections of the stereoscopically triangulated 70 coronal loops in AR 10 955 observed on 9 May 2007 in three filters (171 Å = blue; 195 Å = red; 284 Å = yellow). The observed projection in the $x$–$y$ image plane seen from spacecraft A is shown in the bottom left panel, the projection into the $x$–$z$ plane is shown in the top left panel, and the projection into the $y$–$z$ plane is shown in the bottom right panel. The three orthogonal projections correspond to rotations by 90° to the north or west (to positions indicated on the solar sphere in the top right panel) (Aschwanden et al., 2009a).